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MATERIALS RESEARCH LABORATORIES

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REPORT

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THE EFFECT OF SWITCH RESISTANCE ON THE RINGDOWN OF A SLAPPER DETONATOR FIRESET

D.D. Richardson

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An analysis is performed of the effect of a switch with time-dependent resistance on the ringdown characteristics of a slapper detonator fireset circuit. The latter is represented as a series LRC circuit. The analysis is performed by numerically solving the circuit equation to give the current as a function of time. Several different switch closure characteristics are considered in order to demonstrate their effect on the ringdown behaviour. The results show that ringdown amplitude is significantly affected, and oscillation frequency can be decreased. The magnitude of both effects depends on the switch resistance behaviour after closure. It is shown that significant errors can occur in the estimates of constant circuit inductance and resistance, if the switch resistance is not considered. The implications of improper switch design on slapper detonator functioning are discussed.

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An analysis is performed of the effect of a switch with time-dependent resistance on the ringdown characteristics of a slapper detonator fireset circuit. The latter is represented as a series LRC circuit. The analysis is performed by numerically solving the circuit equation to give the current as a function of time. Several different switch closure characteristics are considered in order to demonstrate their effect on the ringdown behaviour. The results show that ringdown amplitude is significantly affected, and oscillation frequency can be decreased. The magnitude of both effects depends on the switch resistance behaviour after closure. It is shown that significant errors can occur in the estimates of constant circuit inductance and resistance, if the switch resistance is not considered. The implications of improper switch design on slapper detonator functioning are discussed.

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CONTENTS

THE EFFECT OF SWITCH RESISTANCE ON THE RINGDOWN OF A SLAPPER DETONATOR FIRESET

1. INTRODUCTION

Slapper detonators are known to function correctly only under very special electrical conditions. The electrical pulse which bursts the bridge foil to accelerate the flyer plate must have a very short rise time and be capable of delivering enough energy into the bridge to drive the flyer plate to a velocity high enough to initiate the acceptor explosive on impact. This energy must be delivered in times comparable to the width of the voltage spike at burst, or it is wasted. These times, for small bridge slapper detonators, are typically a few tens of nanoseconds. Such short pulses can only be produced by an electrical circuit with low resistance, and extremely low inductance. Typical values for L, R and C are 40 nH, 150 mΩ and 0.25 μF. A circuit which has characteristics typical of these must be switched in such a way that the switch does not dominate circuit behaviour by having a significantly large resistance or inductance. In this report we study the effect of a time dependant switch resistance on the usual method for characterising the fireset.

The circuit of a slapper detonator fireset system normally can be considered as a series LRC circuit with a switch and an exploding foil bridge as extra time dependent components. In recent years it has become popular to estimate the time-independent circuit parameters (inductance L, resistance R and capacitance C) of these fireset circuits by performing a ringdown. This is done by short-circuiting the bridge, closing the switch, and discharging the firing capacitor through the circuit. The current waveform is measured. The analysis of this waveform relies on L,R and C remaining constant in time, so that the frequency of oscillation and the rate of damping of the under-damped oscillations of the circuit are given by the simple expressions resulting from the application of Kirchhoff's voltage law to the circuit.

In practice, it has often been found difficult, for example, to fit the maxima in the ringdown characteristic to the simple exponential decay curve expected. This is thought to result from the fact that the switch used in the circuit makes a time-dependent contribution to the circuit equation. In its simplest form this means that on closure the switch does not instantly drop in resistance from an infinitely large value to zero. Instead, there is a finite time during which the switch resistance is falling to its steady closed-state value, which we will assume here is zero ohms. (If it has a non-zero final state resistance, it can be included in the constant circuit resistance, R.)

The manner in which the switch resistance changes as a function of time will be dependent on the type of switch used. One might expect a vacuum spark gap switch to have a different "closure characteristic" from a gas-filled spark gap, or a shock conduction switch, for example. We will not treat any specific characteristic in this report, as they are not generally known, but rather will perform an analysis to show the effect of time-dependent switch resistance on the shape and magnitude of the ringdown curve. We have found that the effect can be highly significant, and simple analysis of the ringdown curve can lead to spurious conclusions concerning the values of L, R and C. We show that there is no justification for the assumption made by some workers that the effect of the switch can be ignored if one does the analysis for R, L and C on later oscillations in the ringdown, at times longer than the expected full closure time of the switch: the switch closure time affects the entire ringdown characteristic. This observation also has critical implications for the proper functioning of slapper detonators.

In what follows we present our calculations and their outcome. This is followed by a discussion of the significance of the results. Conclusions are made concerning the validity of ringdown measurements and how they should be treated.

2. CALCULATIONS AND RESULTS

A series LRC circuit with a time-dependent switch resistance $R'(t)$ has the following equation, according to Kirchhoff's voltage law,

$$L\frac{dI}{dt} + (R+R'(t))I + \frac{1}{C}\left[\int_0^t I dt + Q_o\right] = 0 \qquad (1)$$

where I = current
t = time
Q_o = initial charge on capacitor C.

Differentiating with respect to time gives the second order ordinary differential equation

$$L\frac{d^2I}{dt^2} + (R+R'(t))\frac{dI}{dt} + \frac{IdR'(t)}{dt} + \frac{I}{C} = 0 \qquad (2)$$

which can be solved as an initial value problem to yield the circuit current-time behaviour.

A simple series LRC circuit can be analysed by assuming that $R'(t)$ and its time derivative are both zero in eqn (2). This allows an analytic solution of eqn (2) of the form [1]

$$I(t) = I_o \sin(\omega t)e^{-\alpha t} \tag{3}$$

where

$$\omega = \sqrt{\frac{1}{LC} - \left\{\frac{R}{2L}\right\}^2} \tag{4}$$

$$\alpha = \frac{R}{2L} \tag{5}$$

$$I_o = \frac{V_o}{\omega L} \tag{6}$$

for an initial voltage $V_o = Q_o/C$ on the capacitor. This is the solution for an under-damped oscillator, which, from eqn (4), satisfies the condition

$$\frac{1}{LC} > \left\{\frac{R}{2L}\right\}^2. \tag{7}$$

The more general equation, eqn (2), cannot normally be solved analytically for time dependent R', and must be treated numerically. We have solved eqn (2) by expressing it as a system of two first order differential equations,

$$\frac{dI}{dt} = W$$

$$L\frac{dW}{dt} + (R+R'(t))W + I\left\{\frac{dR'(t)}{dt} + \frac{1}{C}\right\} = 0 \tag{8}$$

with initial values

$$\begin{aligned} I(0) &= 0 \\ W(0) &= V_o/L. \end{aligned} \tag{9}$$

The latter condition on $W(0)$ is obtained from eqn (1) when $I(0)=0$, and is therefore quite general.

The initial value problem described by eqns (8) and (9) was solved using a simple 4th order Runge-Kutta method [2]. The calculations were performed on a small microcomputer, though accuracy was checked on a VAX 11/780.

The effect of the closing switch was simulated by two different functions. Since the precise characteristic of real switches on closure is unknown, we have chosen two simple forms for computational convenience. One assumed an instantaneous drop in resistance from infinity to some value R_o, and then a linear fall in resistance to zero in a time period t_R. That is,

$$R'(t) = R_o \frac{(t_R - t)}{t_R} \qquad t<t_R$$

$$= 0 \qquad t>t_R. \qquad (10)$$

The other function also assumed an instanteous drop in resistance from infinity to some value R_o, after which the switch resistance remained constant for a time t_R, after which it instantaneously fell to zero. That is,

$$R'(t) = R_o \qquad t<t_R$$

$$= 0 \qquad t>t_R. \qquad (11)$$

Calculations were performed for approximately one and a half periods, for a range of values of R_o and t_R in eqns (10) and (11). Reasonable accuracy was obtained for a time step of 1 ns, though most calculations were checked at 0.5 ns.

The results are given in Figure 1, which shows ringdown curves for the ideal switch (R_o=0 for all t>0), for three combinations of R_o and t_R in eqn (10), and one set of parameters in eqn (11). The values used are shown in the figure.

The immediately obvious result from Figure 1 is that the switch has a significant effect on the amplitude of the oscillations, and to a lesser extent on the frequency. All of the examples shown indicate severe reductions in vibration amplitude, and varying degrees of change in period. The example using eqn (11), the constant resistance case, showed greatest deviations (curve e of Figure 1).

The normal procedure for extraction of the constant circuit resistance and inductance from the ringdown characteristic is to make use of the ideal circuit analytic solution, eqn (3), to obtain these from the first two positive peak values, I_1 and I_2, and the period of oscillation, T_d. Analysis of eqn (3) gives

$$L = \frac{T_d^2}{C} \left\{ 4\pi^2 + \left[\ln \frac{I_1}{I_2} \right]^2 \right\}^{-1} \qquad (12)$$

and

$$R = \frac{2L}{T_d} \ln \frac{I_1}{I_2} . \qquad (13)$$

Eqns (12) and (13) have been applied to all the ringdown curves shown in Figure 1 in order to assess their accuracy when they are applied to situations where there is a non-ideal switch. The estimated values of L and R are given in Table I. A constant, known capacitance of 0.25 μF, resistance of 0.15 Ω and inductance of 40 nH was assumed, being typical of the values normally used.

Table I shows that variations in measured period can occur. It also shows that the accuracy in the determination of values for L and R is dependent on the switch behaviour. For the worst case studied here, (the use of eqn (11) with $R_0 = 0.4\Omega$, $t_R = 300$ ns), the error in estimating L was at least 14%, and that for R was 60%. Smaller, but still significant errors occurred for the other non-ideal switch examples considered, as shown in the Table. A close look at eqns (12) and (13) shows that an underestimation of the period, T_d, causes a lower estimate of both L and R. An increase of the ratio I_1/I_2 has little effect on L since the natural logarithm term in eqn (12) is usually much smaller that the $4\pi^2$ term. A decrease in the ratio does cause R to decrease, however.

TABLE I

"Measured" Estimates of L and R from Ringdown Curves

Assuming C = 0.25 μF

R'(t)	R_0 (Ω)	t_R (ns)	I_1 (A)	I_2 (A)	T_d (ns)	L (nH)	R (mΩ)
eqn (10)	0	-	4810	1456	640	40.3	149
	0.2	100	4000	1212	630	38.8	147
	0.4	100	3370	1021	630	38.8	147
	0.4	300	3030	776	640	39.7	169
eqn (11)	0.4	300	2898	464	700	45.8	240

Note, from eqn (1) that the total circuit resistance at any time is R + R'(t). Actual values for L and R were 40 nH, 150 mΩ.

3. CONCLUSIONS

A simple analysis of the behaviour of a series LRC circuit with a non-ideal switch has been undertaken. It has been found that a real switch will significantly alter the ringdown characteristic that is measured, typically leading to higher damping of the oscillations. Departures from exponential decay occur, as do changes to the oscillation period. These effects are seen to alter the entire ringdown characteristic, not just that part which occurs while the switch has a time-varying resistance.

Our results indicate that extreme caution is required when analysing ringdown curves. Since the characteristics of the switch are not generally known, it is not normally safe to ignore switch effects. We therefore conclude that normal ringdown analysis using eqns (12) and (13) may lead to considerable errors.

A more satisfactory approach would be in some sense to "invert" the ringdown curve to separate switch properties from the rest of the circuit. That is, perform an analysis which provides a curve of $R'(t)$ independent of the other circuit properties. Unfortunately there does not appear to be any ready method for doing this, as in general the presence of R' leads to non-linear differential equations.

It should be noted, however, that provided the measurement is accurate and reliable, it is possible to obtain an alternative estimate for L which is much less sensitive to switch properties. This may be done by measuring the slope of the ringdown curve just after switch activation. In this case our equations show that the slope is given by the second part of eqns (9),

$$W(0) = \left.\frac{dI}{dt}\right|_{t=0} = \frac{V_o}{L} . \qquad (14)$$

An accurate measurement of this slope (the initial rate of rise of current) produces a simple estimate of L. The curves shown in Figure 1 confirm this, since all the curves have the same initial slope.

Unfortunately we know of no correspondingly simple alternate method for estimating the constant R. It may be possible to obtain it from some other technique, for example by measurement of the energy absorbed from an inductively coupled RF radiator into the open-circuit fireset, to obtain a measure of the open circuit resonance behaviour. Knowing L and C, it should be possible to obtain R from the resonance peak.

It should be noted at this point that we have ignored in the present work any effect of time-dependent inductance or capacitance in the switch. If these exist, the matter will be further complicated, though a treatment similar to that given here could be used to assess its importance.

Finally, we note that apart from its importance in circuit analysis, the switch behaviour can have critical effects on the actual functioning of a slapper detonator. The curves of Figure 1 show that significant absorption of energy can take place in the switch, thereby reducing the amount available for bursting the slapper bridge and hence accelerating the flyer plate. Thus, for proper slapper detonator operation, the use of a switch which reduces to insignificant resistance on closure in times which are short relative to bridge burst times is extremely important. Burst time is typically one quarter of the ringdown oscillation period, so closure times must be much shorter than this time which is typically less than a few hundred nanoseconds.* As cold bridge resistance is typically a few tens of milliohms, it will be seen that switch design is exceptionally stringent, but very important. Inadequate switching can cause detonator failure.

4. REFERENCES

1. Resnick, R. and Halliday,D. 'Physics', Wiley International Edition, NY, 1966.

2. Conte, S.D. 'Elementary Numerical Analysis', McGraw-Hill, NY, 1965.

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* In practice, there is always a delay between the switching "signal" being made, and the start of switch closure. The portion of this delay during which current is conducted, plus actual switch closure time should be much less than a quarter of the ringdown period.

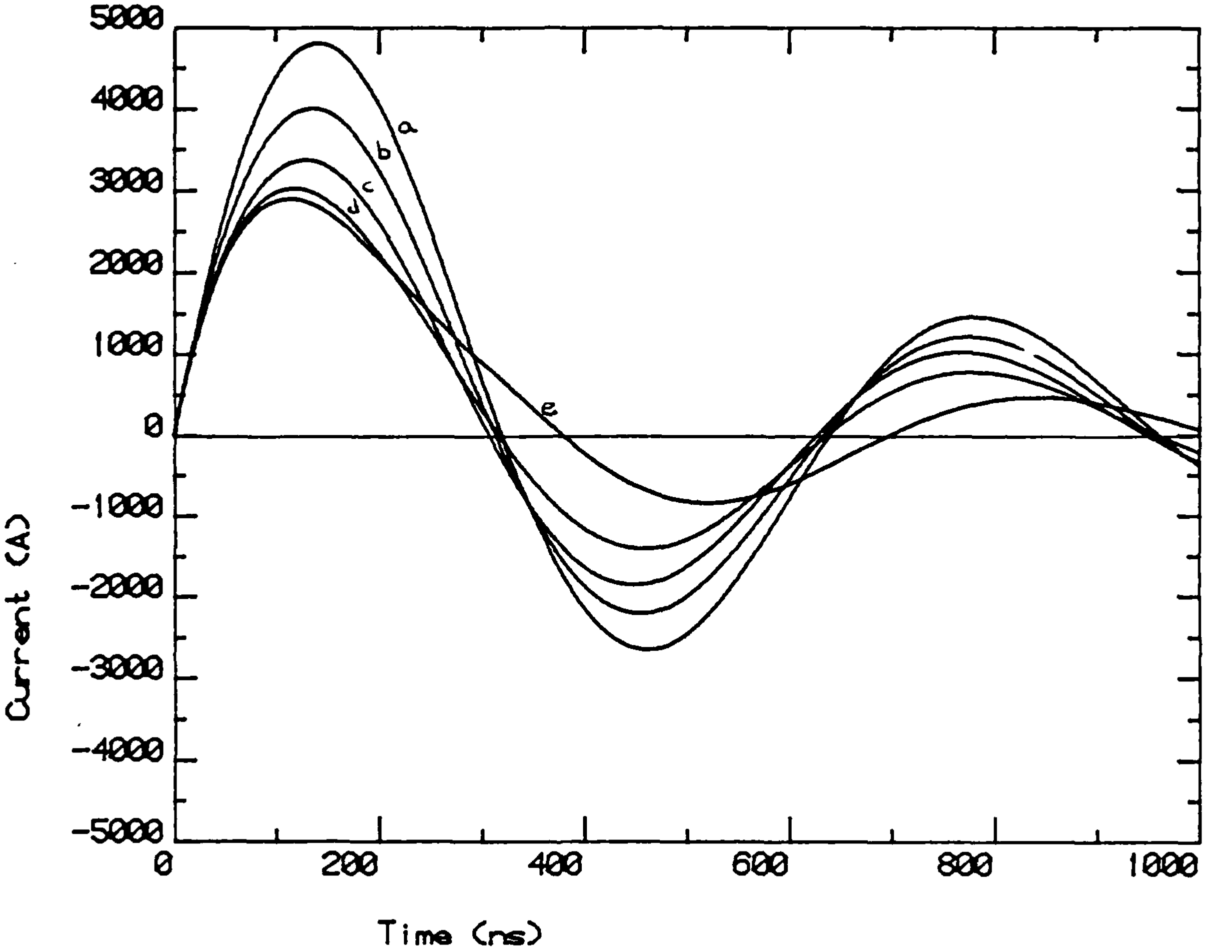

FIGURE 1 Calculated ringdown characteristics for an LRC circuit with a switch. Fixed circuit parameters used are: $R = 0.15\ \Omega$, $L = 40$ nH, $C = 0.25\ \mu F$, $V_o = 2500$ V. The curves shown are for the following switch characteristics.

(a)	Ideal circuit with zero switch resistance	
(b)	Eqn. (10), $R_o = 0.2\Omega$	$t_R = 100$ ns
(c)	Eqn. (10), $R_o = 0.4\Omega$	$t_R = 100$ ns
(d)	Eqn. (10), $R_o = 0.4\Omega$	$t_R = 300$ ns
(e)	Eqn. (11), $R_o = 0.4\Omega$	$t_R = 300$ ns

Cases (b), (c) and (d) are for a ramped linear drop in resistance of the switch, while case (e) is for a constant switch resistance for time t_R.